Analysis of Active SFCL by Design of Control Strategies for Fault Detection and PWM Converter and Protection Coordination with Distance Relay

Ahmad Ghafari Gusheh[1] ,Morteza Razza[2] ,
S. Ghodratollah Seifossadat[3] ,S. Saeedollah Mortazavi[4]
1- Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
Email: Ahmad_ghafari@yahoo.com
2- Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
Email: razzaz_m@cua.ac.ir
3- Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
Email: seifossadat@yahoo.com
4- Department of Electrical Engineering, Shahid Chamran University of Ahvaz, Ahvaz, Iran.
Email: mortazavi_s@scu.ac.ir

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ABSTRACT:
In this paper, the influence on the voltage compensation type, active superconducting fault current limiter (ASFCL) is investigated under symmetrical and asymmetrical fault conditions. ASFCL is consisting of three air-core superconducting transformers and a three-phase voltage source converter. In the normal (no fault) state, the flux in air core is compensated to zero, so the ASFCL has no influence on the main circuit. In the case of short circuit, by controlling the amplitude and phase angle of the second winding's current, the limiting impedance which is in series with the AC main circuit can be regulated, and the fault current will be limited to a certain level. Control strategies consist of fault detection and PWM converter operation is designed. To simplify the design of controllers the mathematical equations can be expressed in synchronous rotating d-q frame. Furthermore, under the condition that the active SFCL is placed behind the relay element, its current-limiting impedance will be added into the measured impedance between the relay and the fault points. As a result, in order to prevent the refused operation of the relay, According to the two different operation modes of the active SFCL, in this paper present the corresponding two modified formulas. Using MATLAB SIMULINK, model of the three phase AC system with ASFCL is created and control strategies test, fault current limiting test, and distance relay operation is investigated.

KEYWORDS: Active SFCL, Superconducting Transformer, Fault detection, PWM inverter, Distance Relay.

1. INTRODUCTION

In recent years, with the great development of interconnected power grid, the power network structure becomes increasingly complicated, and the system short circuit capacity and short circuit current have reached a new level which could exceed the allowable currents of the circuit breakers. The increase of the fault current has imposed a severe burden on the related machinery in the grid, and the stability of the power system is also damaged. The fault current limiters (FCL) are regarded as the suitable solution to solve excessive fault current problems. [1]

Active superconducting fault current limiter (ASFCL) voltage compensation type is a novel topology of FCL. This type SFCL not only preserves the merits of bridge type SFCL such as the automatic switch to the current limiting mode and without the quench of the superconductor, but also has the particular abilities of controlling the steady fault current and compensating active and reactive power for AC main circuit in the normal state. Fig. 1 shows the circuit structure of the three phase active SFCL, which is consisting of three air-core superconducting transformers and a three-phase voltage source converter. [2]

The primary winding on the air-core superconducting transformer is in series with AC main circuit, and the second winding is connected through a converter. In normal (no fault) operating state, the flux in air core is compensated to zero, so the ASFCL has no influence on the main circuit. In the case of short circuit, by controlling the amplitude and phase angle of the second winding's current, the limiting impedance which is in series with the AC main circuit can be regulated, and the fault current will be limited to a certain level. [3]

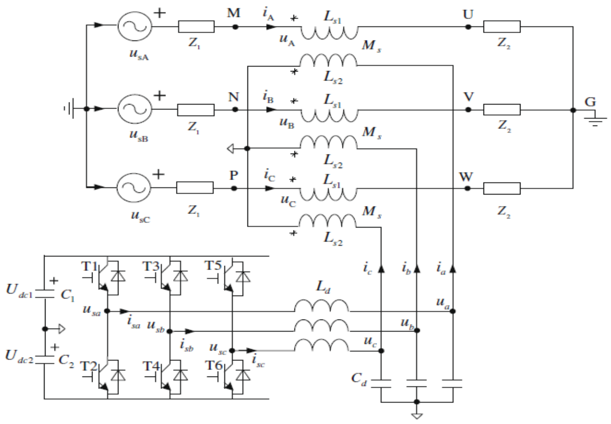

Fig. 1. Circuit structure of the three phase ASFCL in AC system

In this paper, control strategies for fault detection and operation of PWM inverter is designed. To simplify the design of controllers, the system currents can be expressed in synchronous rotating d-q frame. Also, under the condition that the active SFCL is placed behind the relay element, its current-limiting impedance will be added into the measured impedance between the relay and the fault points. As a result, in order to prevent the refused operation of the relay, the measured impedance should be revised.

According to the two different operation modes of the active SFCL, this paper presents the corresponding two modified formulas. [4]

2. STRUCTURE AND PRINCIPLE OF THE ACTIVE SFCL

Fig. 1 shows the circuit structure of the three phase voltage compensation type active SFCL, which is composed of an air-core superconducting transformers, a three-phase 48-pulse GTO converter and DC-DC chopper. The air-core superconducting transformer has some advantages such as absence of iron losses and magnetic saturation, and it has greater possibility of reduction in size and weight than the conventional and the iron-core superconducting transformer.

The primary winding of the air-core superconducting transformer is in series with AC main circuit, and the second winding is connected through a converter.

The equivalent circuit of the air-core superconducting transformer is shown as in Fig. 2.

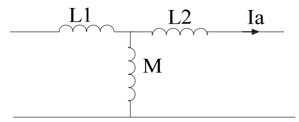

Fig. 2. Equivalent circuit of the air-core superconducting transformer

By neglecting losses of the air-core superconducting transformer, the voltage equation of the transformer is expressed as follows:

$$U_A = j\omega L_{S1} I_A - j\omega M_S I_a \tag{1}$$

That $L_{S1} = L_1 + M_S$

In normal operation state, Controlling I_a to make $j\omega L_{S1} I_A - j\omega M_S I_a = 0$ and the A-phase superconducting transformer's primary voltage uA will be regulated to zero. Thereby, the SFCL will have no influence on phase A, and I_a can be set as:

$$I_a = \frac{L_{s1}}{M_S} I_A = \frac{L_{s1}}{M_S}\left(\frac{U_{SA}}{Z_1 + Z_2}\right) \tag{2}$$

When the single-phase fault happens, the line current will rise from I_A to I_{Af}.

$$I_{Af} = \frac{U_{SA} - U_{Af}}{Z_1} \quad , \quad U_{Af} = j\omega L_{S1} I_{Af} - j\omega M_S I_a \tag{3}$$

So,

$$I_{Af} = \frac{U_{SA} + j\omega M_S I_a}{Z_1 + j\omega L_{S1}} \tag{4}$$

That U_{SA} is the source voltage and U_{Af} is the primary voltage of the superconducting transformer in the fault conditions.

Also, the primary and secondary voltages of the A-phase superconducting transformer will increased to U_{Af} and U_{af}, respectively:

$$U_{Af} = j\omega L_{S1} I_{Af} - j\omega M_S I_a = \frac{U_{SA}(j\omega L_{S1}) - (j\omega M_S) Z_1 I_a}{Z_1 + j\omega L_{S1}} \tag{5}$$

$$U_{af} = j\omega L_{S2} I_a - j\omega M_S I_{Af} = j\omega L_{S2} I_a - (j\omega M_S)\frac{U_{SA} + (j\omega M_S) I_a}{Z_1 + j\omega L_{S1}} \tag{6}$$

From Eq. (4), it is observed that the primary voltage can be adjusted by regulating Ia, and the current-limiting impedance Z_{ASFCL} can be controlled in Eq. (7):

$$Z_{ASFCL} = \frac{U_{Af}}{I_{Af}} = j\omega L_{S1} - \frac{j\omega M_S I_a (Z_1 + j\omega L_{S1})}{U_{SA} + j\omega M_S I_a} \tag{7}$$

According to the difference in the regulating objectives of I_a, there are two operation modes:

Mode1: This mode includes time of fault detection and operation of the converter, in this mode I_a remain to original state (Eq. (2)), that I_{Af-1} can be achieved by:

$$I_{Af-1} = \frac{U_{SA} + j\omega L_{S1} I_A}{Z_1 + j\omega L_{S1}} \tag{8}$$

Mode2: Regulating the phase angle of I_a to make the angle difference between U_{SA} and $j\omega M_S I_a$ be 180^0 that I_{Af-2} can be achieved by :

$$I_{Af-2} = \frac{U_{SA} - \omega M_S |I_a|}{Z_1 + j\omega L_{S1}} \tag{9}$$

Because of $I_{Af-2} < I_{Af-1}$ the value of limiting impedance in mode 2 is larger than that in mode 1, as a result of the better limiting effect.

3. CONTROL STRATEGY FOR FAULT DETECTION AND VOLTAGE SOURCE CONVERTER

To design an appropriate control system Firstly, design a control strategy for fault detection and determine the operation mode of voltage source converter, then the control strategy for converter is designed.

The control strategy for fault detection and determine the operation mode of AFLC is shown in Fig. 3.

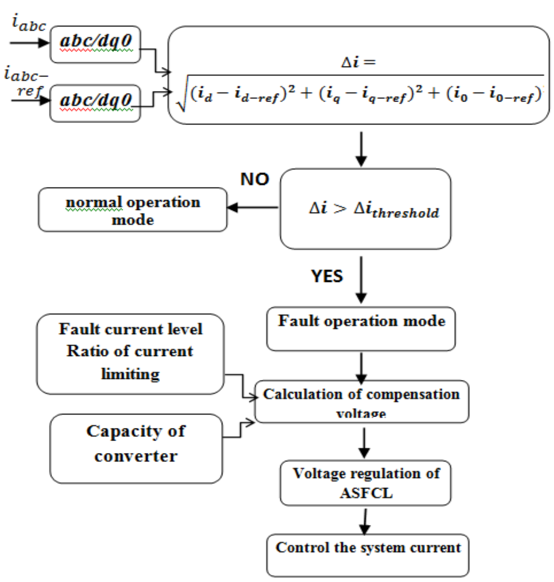

Fig. 3. Control strategy for fault detection and determine the operation mode

To simplify the design of controller, the system currents can be expressed in synchronous rotating d-q frame. According to the comparison between the instantaneous system current (i_d , i_q ,i_0) and the long-term steady-state value of the system current (i_{d-ref} , i_{q-ref} ,i_{0-ref}), the fault current level can be estimated. Then, the value of compensation voltage can be calculated within the energy storage capacity. With the coordinate operation of the converter and chopper, the AFLC can output the compensation voltage in series with the main circuit, and the system current can be controlled actively.[1]

According to Fig.1, the current and voltage equations can be achieved by:

$$\begin{cases} L_d \dfrac{di_{sa}}{dt} = u_{sa} - u_a \\ L_d \dfrac{di_{sb}}{dt} = u_{sb} - u_b \\ L_d \dfrac{di_{sc}}{dt} = u_{sc} - u_c \end{cases} \tag{10}$$

$$\begin{cases} C_d \dfrac{du_a}{dt} = i_{sa} - i_a \\ C_d \dfrac{du_b}{dt} = i_{sb} - i_b \\ C_d \dfrac{du_c}{dt} = i_{sc} - i_c \end{cases} \tag{11}$$

Further, the mathematical equations in dq0 reference frame can be obtained by:

$$\begin{cases} L_d \dfrac{di_{sd}}{dt} = \omega L_d i_{sq} + u_{sd} - u_d \\ L_d \dfrac{di_{sq}}{dt} = -\omega L_d i_{sd} + u_{sq} - u_q \\ L_d \dfrac{di_{s0}}{dt} = u_{s0} - u_0 \end{cases} \tag{12}$$

$$\begin{cases} C_d \dfrac{du_d}{dt} = \omega C_d u_q + i_{sd} - i_d \\ C_d \dfrac{du_q}{dt} = -\omega C_d u_d + i_{sq} - i_q \\ C_d \dfrac{du_0}{dt} = i_{s0} - i_0 \end{cases} \tag{13}$$

The DC link voltage equation can be achieved by:

$$u_{dc1} + u_{dc2} = u_{dc} \tag{14}$$

$$C_2 \frac{du_{dc2}}{dt} - C_1 \frac{du_{dc1}}{dt} = 3(i_0 + C_d \frac{du_0}{dt}) \tag{15}$$

The control system diagram of the three phase converter is shown as Fig. 4. According to the operating state of the main circuit and the current-limiting mode of the ASFCL, the current reference signals ($I_{abc-ref}$) can be known. Further, based on Eq. (6), the reference signals ($U_{abc-ref}$) will be obtained, and then the voltage reference signals of the converter ($U_{dq0-ref}$) can be achieved.[3]

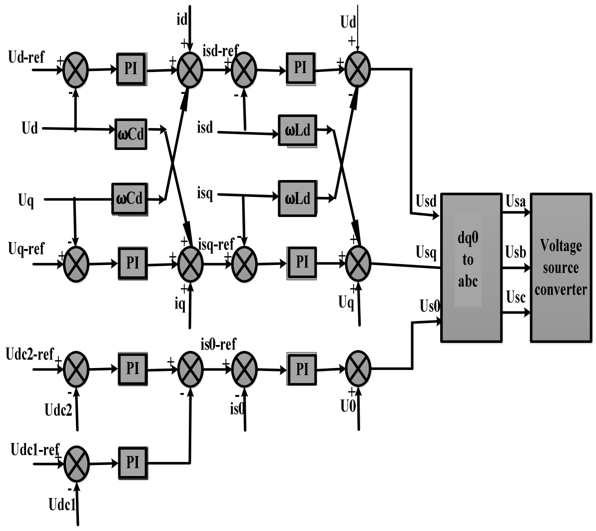

Fig. 4. Control strategy for three phase PWM converter

4. DISTANCE RELAY OPERATION IN PRESENCE OF THE ASFCL

The dual-source power system with the active SFCL is given, as shown in Fig.5. E_A and E_B denote the system supplies at the line ends, respectively.[4],[6]

Z_{AB} is the impedance of the line AB (L=200Km, $|Z_{AB}|$ = 59 Ω), and p is per unit length of the line section between the fault and the relay points.

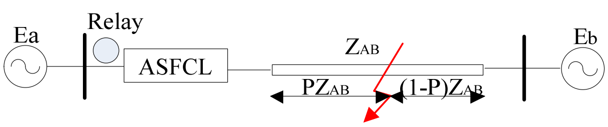

Fig. 5. Distance relay with ASFCL in power system

The measured impedance by the distance relay with and without ASFCL can be achieved by:

$$Z_{R-withoutsfcl} = PZ_{AB} \quad (16)$$

$$Z_{R-withsfcl} = PZ_{AB} + Z_{ASFCL} \quad (17)$$

To ensure the correct operation of relay, it is need to eliminate the current-limiting impedance from the measured impedance.

When the active SFCL operates under mode 1 or mode 2, as the current limiting impedance will have a certain relationship with PZ_{AB} (corresponding to Z_1 in the previous impedance expression) and $(1-P)Z_{AB}$ (corresponding to Z_2). The impedance Z_{R-1} and Z_{R-2} can be shown as:

$$Z_{R-1} = \frac{(1-P)Z_{AB}}{K_1} \quad (18)$$

$$Z_{R-2} = \frac{1}{1-K_2}(PZ_{AB} + j\omega L_{S1}) \quad (19)$$

That K_1 and K_2 can be obtained by:

$$K_1 = \frac{Z_{AB} + j\omega L_{S1}}{j\omega L_{S1}}, \quad K_2 = \left|\frac{\omega L_{S1}}{Z_{AB}}\right| \quad (20)$$

Therefore, the actual length of the line section between the fault and the relay points can be according to the modification value Z'_{R-1} and Z'_{R-2} :

$$Z'_{R-1} = \frac{K_1 Z_{R-1} - Z_{AB}}{K_1 - 1} = PZ_{AB} \quad (21)$$

$$Z'_{R-2} = (1-K_2)Z_{R-2} - j\omega L_{S1} \quad (22)$$

5. MATLAB SIMULATIONS

To evaluate the effectiveness of this SFCL, the model as shown in Fig. 1 is created in MATLAB. The simulation parameters of the circuit are expressed in Table 1.

Table 1. Parameters of simulated system

Item	Parameters
U_{SA}	220V
Z_1	0.19+2.16iΩ
Z_2	15+2iΩ
f	50Hz
L_{S1}=L_{S2}	10mH
M_S	9mH
C_1=C_2	2000μF
U_{dc}	600V
L_f	6mH
C_f	30μF

5.1. Control Strategies Test

To evaluate the control strategies test can be assumed that the fault occurs at time t = 0.2s.

Figure 6 and 7 show the dq0 currents in three phase and single phase fault conditions, respectively. The time delay of fault detection and converter operation is 20ms. In this time the compensator operate in mode 1.

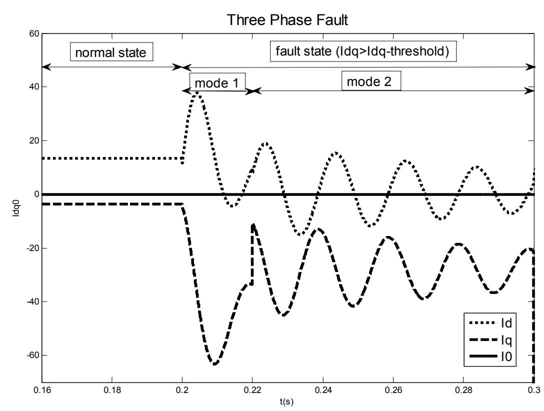

Fig. 6. I_{dq0} (Three phase fault)

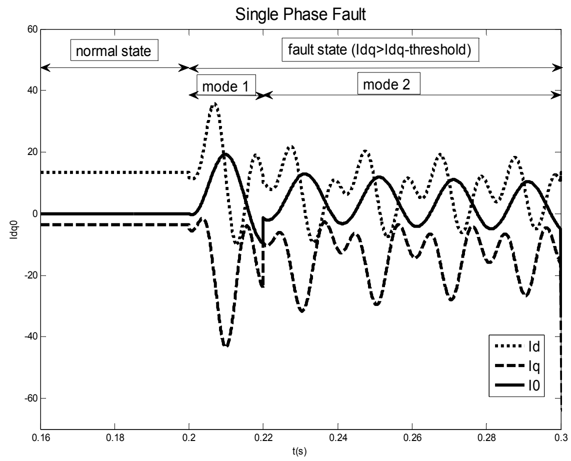

Fig. 7. I_{dq0} (Single phase fault)

Figure 8,9,10 shows the Iabc-ref in normal state, single phase fault and three phase fault respectively.

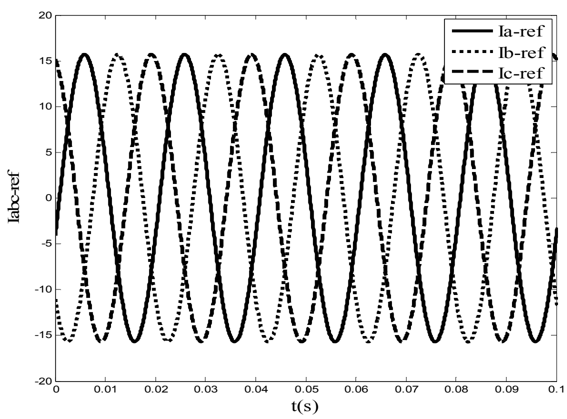

Fig. 8. $I_{abc-ref}$ in normal state

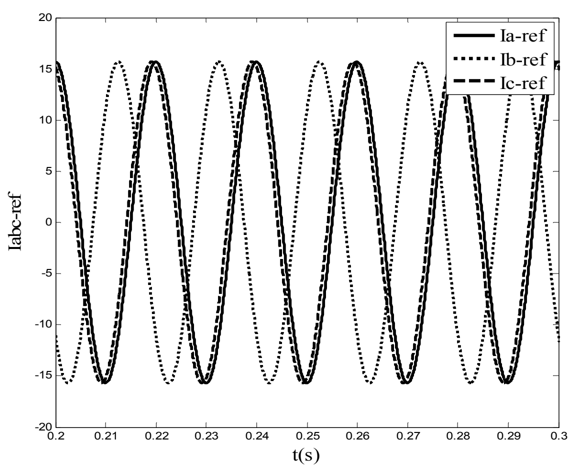

Fig. 9. $I_{abc-ref}$ in single phase fault condition

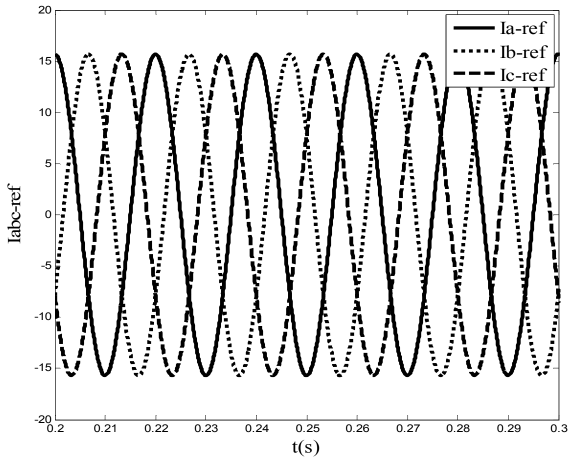

Fig. 10. $I_{abc-ref}$ in three phase fault condition

According to results can be seen that the reference currents in normal state and three phase fault are symmetrical currents and in single phase fault condition are asymmetrical currents, that show the accurate operation of PWM converter control strategy in symmetrical and asymmetrical fault conditions.

Fig. 11 shows the voltage of the split DC link capacitors under the single-phase fault. After the injected current i_a is regulated by the converter, the each capacitor voltage will be composed of two parts. One is the initial DC component, whose value is 300 V, and the other is the AC component with the peak value of 20 V. From Fig. 11, it can be found that the AC components of U_{dc1} and U_{dc2} are opposite with each other, and the total DC voltage can be kept at the level of 600 V.

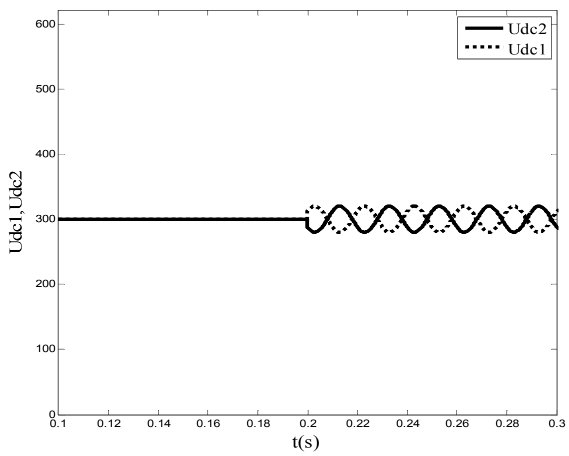

Fig. 11. Voltage of the split DC link capacitors under the single-phase fault

5.2. Fault Current Limiting Test

The comparison of the fault current characteristics without ASFCL and with ASFCL in Mode1 and Mode2 is shown In Fig. 12, we can find Mode 2, which is based on regulating the phase angle, shows the best effect of suppressing fault current.

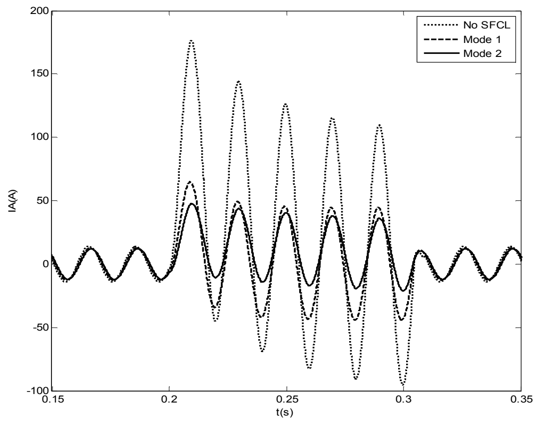

Fig. 12. The comparison of the fault current characteristics in Mode 1 and 2

Fig. 13 shows the curves of $I_{A\text{-}peak}$ with different phase angle and magnitude of compensating current Ia . It is known that the best current limiting effect would be acquired when the phase angle equals to 90 degree. Increasing magnitude of compensating current can improve the current limiting effect.

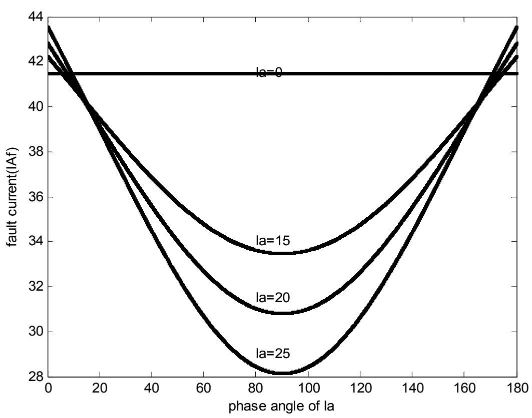

Fig. 13. Relations between $I_{A\text{-}peak}$ and phase of Ia under mode2 ($I_{a\text{-}peak}$ =0A, 15A, 20A, 25A)

Fig. 14 shows the relationship between the peak amplitude of the fault current and the phase of Ia (the amplitudes constant). This waveform is an approximate sine wave, and when the phase of Ia is 90^0, the limiting effect is the best. Besides, three points, which response to mode 1, 2 can also be found in Fig. 14.

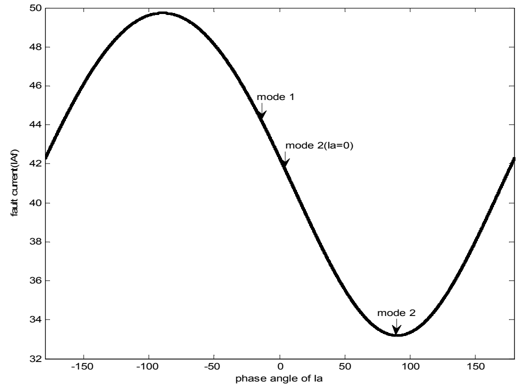

Fig. 14. The phase of current in the second winding

The current characteristics of the seconding winding (I_a) and primary winding (I_A) is shown in Fig. 15.

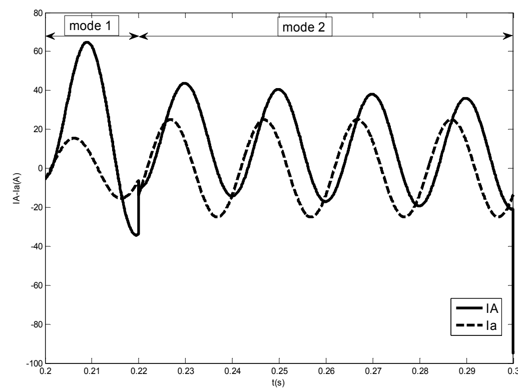

Fig. 15. I_A and I_a in presence of ASFCL

The value of transformer primary and secondary voltages, fault current and limiting impedance are expressed in Table 2.

Table 2. Voltage and current values in different modes

	mode1	mode2			
Ia	15.52∠-15.31	0	15∠90	20∠90	25∠90
$\|u_{af}\|$	111.48	117.25	141.75	149.92	158.1
$\|u_{Af}\|$	125.19	130.28	147.54	153.32	159.1
$\|I_{Af}\|$	44.38	41.47	33.4	30.8	28.15
$\|Z_{ASFCL}\|$	2.82	3.14	4.4	4.98	5.68

5.3. Distance Relay Operation

To evaluate the validities of the proposed modified formulas, the model as shown in Fig. 5 is created in MATLAB.

Fig. 16 and 17 denotes the measured impedance of Relay corresponding to the two modes under the conditions with and without adopting the modified formulas. When the measured impedance is smaller or equal to the setting value Zset (Zset = 0.8ZlAB), the protection element will operate, otherwise it will not take an action.

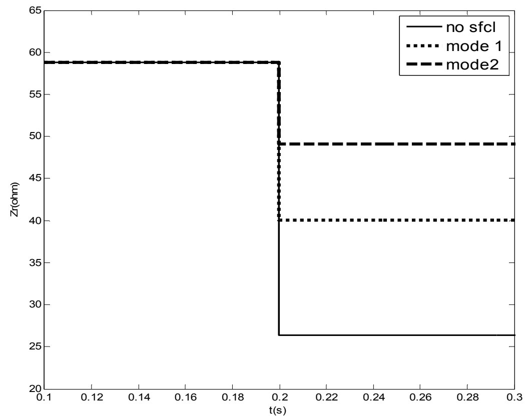

Fig. 16. The measured impedance of Relay corresponding to the two current-limiting modes without using the modified formulas (fault distance=90km)

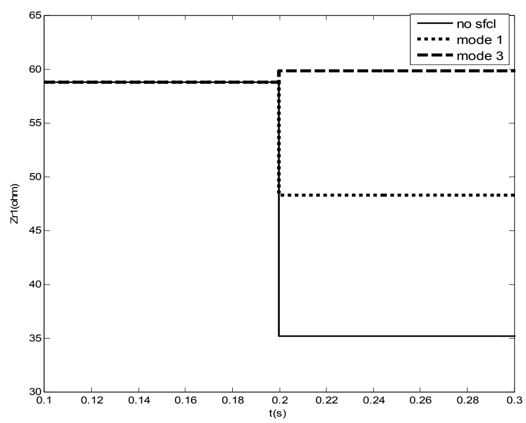

Fig. 17. The measured impedance of R1 corresponding to the two current-limiting modes without using the modified formulas (fault distance=120km)

According to Fig. 16, when the fault distance is merely 90 km, the protection will reject to operate in mode 2, and in the case that the fault distance is 120 km, the measured impedance after the fault will be even bigger than the before in mode 2 and the protection will reject to operate in mode 1 and 2.

Fig. 18 denotes the measured impedance of Relay with adopting the modified formulas.

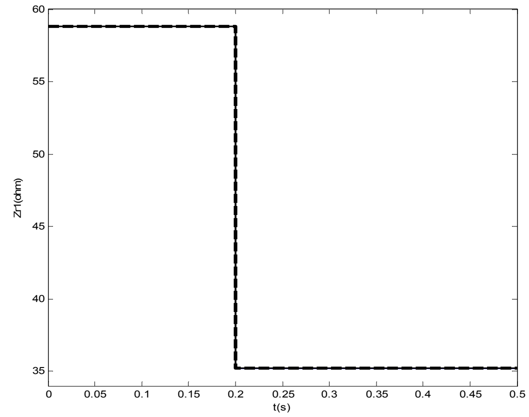

Fig. 18. The measured impedance of Relay with adopting the modified formulas

6. CONCLUSIONS

A new active SFCL is presented in this paper, and its limiting effect is validated by simulations. In normal state, the SFCL has no influence on main circuit. When short fault happens, by regulating the amplitude and phase angle of the current in the second winding, the limiting impedance which is in series with the AC main circuit can be changed, so that the fault current will be controlled to a certain level.

The control strategies for fault detection and PWM converter are designed. It is known that the control strategies are feasible and valid, and the three-phase PWM converter can work well under unsymmetrical and symmetrical fault conditions, and then the fault current can be limited quickly and effectively. In addition, the balance control can make the variation trends of the DC link capacitor-voltages be opposite with each other, as a result of keeping the voltage balance.

The effects of ASFCL on the distance relay protection are investigated. Before using the modified formulas, as the current-limiting impedance is added into the measured impedance, the protection distance will be shorter than the condition without SFCL. For the two operation modes of the ASFCL, the protection distance under the mode 2 will be the shortest. After adopting the proposed two modified formulas, the impacts of the two kinds of current-limiting impedances can all be eliminated, and then the measured impedance can reflect the actual distance between the relay and the fault points.

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